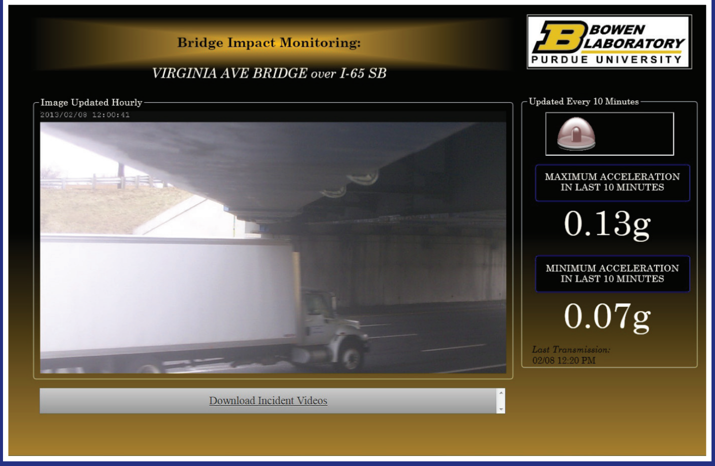
JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Development and Verification of Web-based Bridge Monitoring Interface



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16. Abstract

With the advancement of many off-the-shelf data acquisition systems readily available today and the availability of 3G and 4G high-speed wireless cellular networks, the potential for remote monitoring of critical bridges has never been better. Needs exist regarding scour and general structural response for long-term monitoring. However, short-term monitoring using quickly deployable, rugged systems are also desirable in cases where impact, fire, environmental effects, or other damage may occur. These robust systems can be deployed rapidly, and endure harsh elements, enabling DOTs to constantly assess and monitor a structure, or a network of structures. Hence, the objective of this project is to explore the feasibility and proof of concept of using a web-based bridge monitoring interface for use on selected INDOT bridges for both short-term and long-term applications. This report will focus on a single case study, the Virginia Ave Bridge over I-65 SB, a steel plate girder bridge that frequently falls victim to truck impact as a result of low clearance. This case study is uniquely different and provides insight into how targeted instrumentation systems can be used to probe specific parameters desired by owners for bridge condition assessment and monitoring. It will be shown how commercially available instrumentation systems can be tailored to fit any unique application required. Additionally, it will be demonstrated that INDOT benefited from this specific case of field-deployed, short-term monitoring, which included automated notifications of critical onsite conditions.

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EXECUTIVE SUMMARY

DEVELOPMENT AND VERIFICATION OF WEB-BASED BRIDGE MONITORING INTERFACE

Introduction

Off-the-shelf data acquisition systems have advanced over recent years, becoming readily available, reasonably priced, and more user-friendly. High-speed wireless cellular networks have also been established, offering the potential for remote monitoring as never before. The bridge engineering industry generally accepts the need for long-term monitoring of scour and general structural response of bridges. However, short-term monitoring using quickly deployable, rugged systems is also desirable in cases where impact, fire, environmental effects, or other damage may occur to valued infrastructure. These monitoring systems, coupled with a web-based, real-time data display, can become very effective asset management tools for bridge owners.

The Virginia Avenue Bridge near Indianapolis, Indiana, was selected as the case study to exercise and verify a prototype web-based bridge monitoring system. The superstructure of this bridge is often impact loaded by truck cargo due to its 14-ft. underclearance. Thus, the prototype system was targeted specifically to monitor and alert key personnel of any impacts. Additionally, the monitoring system automatically captured and delivered high definition video footage of the impact event. The prototype was developed with autonomy in mind, requiring minimal supervision, providing versatile capability, enduring severe environmental conditions, and having remote connectivity.

Findings

- Real-time, web-based bridge monitoring systems can be developed using readily-available, off-the-shelf resources. The prototype developed during this project was primarily made up of commercially available components from Campbell Scientific, Inc., Logan, Utah.
- Software based on graphical user interfacing is available providing drag-and-drop methods of creating web-based data displays. This software even enables users who are not trained in website development to create data-rich, effective monitoring displays that can be run from a PC or published to a web server.
- Existing technology, such as wireless cellular service and host email servers, provide effective and reliable platforms to base real-time notification protocols on. Three protocols were developed under this project, including email messaging from the datalogger, text messaging from the datalogger, and email messaging with attachments from the digital camera. Using established technology and methods of wireless communication simplifies implementation and minimizes life cycle costs of the system.

Implementation

Bridge girder impact captured on video footage was the targeted bridge parameter for the prototype monitoring system. However, it should be emphasized that the major components of the prototype system could be adapted for implementation on a variety of bridges, in different and even more remote locations, monitoring entirely diverse parameters of interest (e.g. overload, load distribution, fatigue, pier tilt, temperature, etc.). Furthermore, the web-based user interface can be configured to receive real-time data from a network of dataloggers stationed at different locations throughout the State or Nation. Thus, a single user interface can be made to concurrently display a multitude of data from a number of bridges.

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1. INTRODUCTION

Off-the-shelf data acquisition systems have advanced over recent years, becoming readily available, reasonably priced and more user-friendly. Additionally, 3G and 4G LTE high-speed wireless cellular networks have been established, offering the potential for remote monitoring of critical bridge structures in locations and at levels of reliability, as never before. The bridge engineering industry generally accepts the need for long-term monitoring of scour and general structural response of bridges. However, short-term monitoring using quickly deployable, rugged systems is also desirable in cases where impact, fire, environmental effects, or other damage may occur to valued infrastructure.

These robust systems can be deployed rapidly and endure harsh elements, enabling departments of transportation (DOT) to continuously monitor and assess a structure, or a network of structures for both the short and long term. The objective of this project was to explore the feasibility and proof of concept by using a web-based bridge monitoring interface on a selected Indiana DOT (INDOT) bridge for a short-term application.

The selected bridge was the Virginia Avenue Bridge over I-65 Southbound, seen in Figure 1.1. This paper discusses the method and results of a study which validated the practicality and efficacy of this type of targeted parametric, web-based monitoring of bridges.

The Virginia Avenue Bridge over I-65 Southbound (INDOT Bridge #5720), in Indianapolis, Indiana, was designed by Chase W. Cole & Son Engineers in 1971, using provisions from the 1969 AASHO specifications. Later, deck repairs and railing replacement occurred in the early 1990's. Today, this bridge continues to span 155 ft., with 50 ft. of roadway and two 6 ft. sidewalks, supported on nine 6 ft. deep, A36 steel plate girders. The girders are configured on a 37° skew and are bolt spliced 39 ft. from either end of the span. In May 2003, INDOT and Federal Highway Administration (FHWA) carried out the closure of combined sections of I-65 and I-70 for a rapid rehabilitation of several lane-miles of roadway, numerous bridge decks, as well as multiple bridge deck replacements. The project was named, Hyperfix 65/70. This project closed the interstates for about 55 days, reopening in September of 2003 (*1*). The ambitious Hyperfix 65/70 project accomplished much needed renovation for the deteriorated infrastructure at the time; however, one unintended, deleterious consequence of the project was a reduced vertical underclearance of the Virginia Avenue Bridge. The asphalt pavement overlay reduced the underclearance to approximately 14 ft., leaving little freeboard between the bottom flange of the stout girder and the legal shipping height of 13′6″. As a result of the reduced underclearance, reported truck (term used generally herein to include the truck and/or its cargo) impacts with the bridge increased 11-fold, going from 3 reported impacts prior to Hyperfix 65/70, to 33 reported impacts after; for a total of 36 known impacts, as of July 2012 (*2*).

Figure 1.1 Virginia Avenue Bridge over I-65 SB in Indianapolis, Indiana (southern perspective).

Knowing the history of impacts on the bridge, members of the Study Advisory Committee (SAC) selected the Virginia Avenue Bridge as the principal candidate for SPR-3554. This JTRP project was originally broken down into five primary tasks, namely:

- **Task I:** Development of a General Purpose Web-based Interface
- **Task II:** Development of a Web-based Graphical Condition Notification Interface
- **Task III:** Development of Real-time Notification Protocols
- **Task IV:** Build and Install a Prototype System
- **Task V:** Preparation of a Final Report

Note that the structural monitoring of SPR-3554 was not intended to be "structural health monitoring" in the traditional sense, rather *targeted* monitoring of a specific parameter or parameters. It is also worth noting that at the outset of the study, immediate need arose for implementation of a prototype on the Sherman Minton Bridge over the Ohio River. A prototype web-based monitoring system was successfully implemented to target ambient and steel temperatures, and pier tilt during retrofit operations, providing real-time data capability and automated email notifications for pre-defined alarm conditions. An excerpt about that monitoring system from the Sherman Minton Bridge final report can be seen in Appendix A of the present report. This report focuses on the tasks SPR-3554 completed and verified while monitoring truck impacts on the Virginia Avenue Bridge.

2. TASKS I & II: DEVELOPMENT OF A GENERAL PURPOSE WEB-BASED INTERFACE WITH GRAPHICAL CONDITION NOTIFICATION

Campbell Scientific's RTMC (Real-Time Monitor and Control) Pro software was used to develop a general purpose, web-based user interface (WUI). The WUI was purposefully developed for effortless interaction, as well as to demonstrate the effectiveness that can be had from simplified, data-rich interfaces.

2.1 Discussion of the Web-Based Interface

The use of RTMC Pro is based in the concepts of graphical user interfaces (GUI), which is a powerful concept that has significantly improved the human-computer interaction through using images rather than text commands. This concept is especially enabling for personnel not trained in website programming languages. RTMC Pro software provides the ability to create and run graphical screens to display real-time data collected from remote dataloggers. A screen created within RTMC Pro (see Figure 2.1 for example) can be created, saved, and then displayed using the built-in RTMC Run-time, enabling real-time data viewing on any computer screen, or can be published to a web server. A list of graphical tools is provided and a drag-and-drop methodology is utilized to place each desired component or data display tool on the screen being developed.

Once a component has been placed on the screen, it can then be linked to data files being collected on the PC, or on a server connected to the PC. Any time the RTMC screen is run, or if published to a web server, opened in a browser, the data is automatically updated. Then the screen will automatically continue to update the data displays according to the refresh interval determined by the display creator. The different data displays range from digital to analog and from numbers to charts and more.

Campbell Scientific's CSI Web Server allows the user to view RTMC projects using a web browser. The CSI Web server includes the CSI Web Server Administrator, used to configure the web server, check status of the web server, and browse to sites running on the web server. CSI Web Server also includes the Web Publisher, allowing publication of the RTMC Pro screen to either a PC website using CSI Web Server or to an HTTP enabled datalogger.

Figure 2.2 shows the WUI developed for the Virginia Avenue Bridge monitoring, which was published to a web server. Upon opening the screen in a web browser, the user was provided with immediate understanding of the basic site conditions, as well as status of communication between the web server and the datalogger (see Figure 2.3). The WUI was updated hourly with a current photograph from the camera. This photo provided valuable information relative to the weather conditions and state of the girder, as well as a limited view of road and traffic conditions. Additionally, the website was designed to relay 10-minute maximum and minimum accelerations measured by the accelerometer onsite (discussed more below). This means that every 10 minutes the datalogger would record two data points, the maximum acceleration and the minimum acceleration over the previous 10 minute interval. This data was useful in obtaining an instantaneous awareness of whether or not the girder had been impacted within the last 10 minutes, with the date and time of the latest transmission visible. After observing the maximum and minimum data on the WUI for a couple days it became apparent that in non-impact state, the accelerometer would measure accelerations similar to what is seen in Figure 2.2, between 0.13 g and 0.07 g. Thus, if the webpage was opened and a maximum acceleration in the past 10 minutes was reported as 1.6 g, for example, it could be reasonably assumed that an impact had recently occurred.

Another feature added to WUI was access to the impact, or incident, videos. Each video recorded by the digital camera was stored on a secure server residing at Purdue University. A link, which can be seen below the hourly photo in Figure 2.2, entitled, "Download Incident Videos" was added offering access to the impact videos from any computer or mobile device with an internet connection. Note, however, that the option was exercised to restrict the video files to only those people having secure login credentials. The video files captured by the camera were in .AVI format. Once retrieved from the datalogger, the video file was converted automatically to .MP4 format, a format more widely

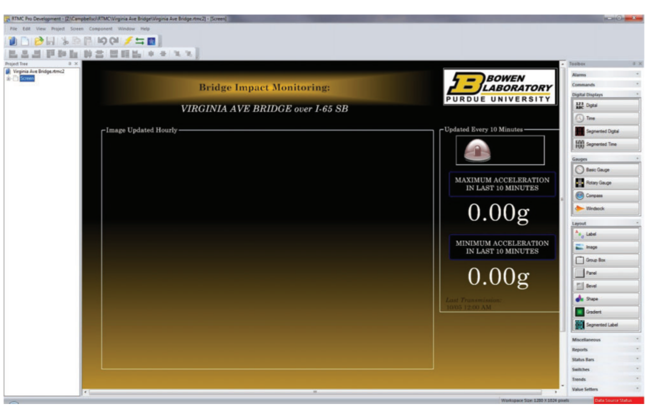


Figure 2.1 Screen shot of Campbell Scientific's RTMC Pro software used to create and run graphical screens, or websites.

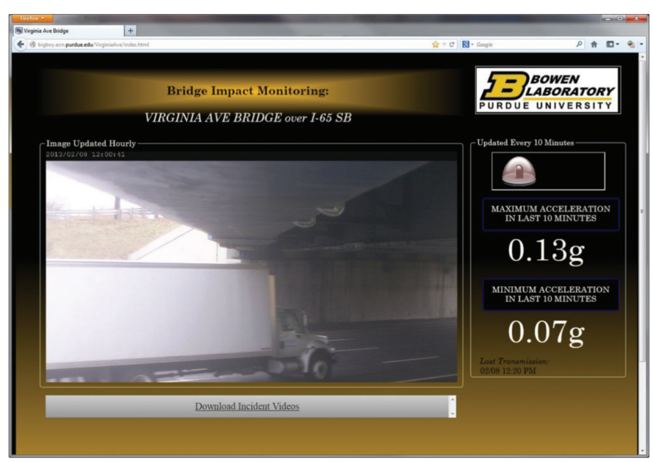


Figure 2.2 Web-based interface providing the user with immediate understanding of onsite conditions and status of the monitoring system.

Figure 2.3 Graphical user interface tools used to report communication status between the server and the remotely located datalogger (located just off the screen in Figure 2.2).

compatible with mobile devices, using an executable (.EXE) application on the Purdue server. The .EXE program periodically scanned the video folder on the server, when a new file was detected it was converted to .MP4 format and then was linked to the WUI. Thus, the impact videos could be accessed by PCs and mobile devices virtually anywhere and at any time. This provided INDOT officials with invaluable understanding of the situation, pertaining to each impact, needed to make important operational and public safety decisions; all within a few minutes of an impact event.

2.2 Conclusion for Development of the Web-Based Monitoring Interface

The WUI developed as part of this study displayed nearly instantaneous (real-time) and continuous data on the worldwide web, supplying understanding of conditions at the monitored site from almost any user location. Further, it showed that user-friendly development software is available "off-the-shelf" that the most inexperienced web builder can use to create an effective and powerful web-based user interface.

3. TASK III: DEVELOPMENT OF REAL-TIME NOTIFICATION PROTOCOLS

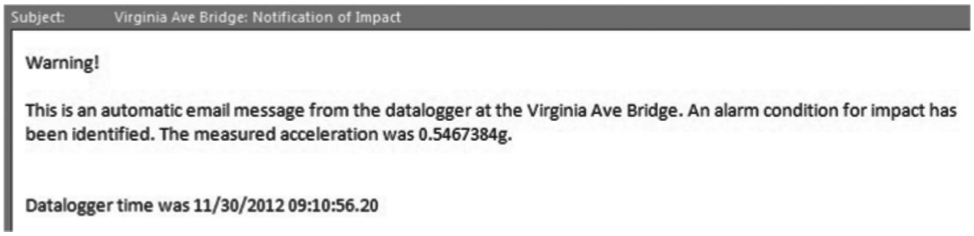
Highly reliable, real-time notification protocols were developed for SPR-3554 providing for immediate warning of an impact at the Virginia Avenue Bridge, near Indianapolis, Indiana. The notification protocols were fully automated using existing commercially available technologies and established methods of wireless communications, simplifying implementation and minimizing life cycle costs.

3.1 Discussion of Real-Time Notification Protocols

Three notification protocols were developed, and shown to be effective and dependable; albeit, only two of the three were extensively used throughout the study. The first protocol developed was email messaging sent from the datalogger, via the wireless modem, through a host email server. Two host email servers were used at different times throughout the project, namely Gmail and Purdue University servers. The Gmail host email service is free of charge for any registered Gmail domain email address. The datalogger was programmed to only send one email for each event. When the accelerometer measured an acceleration value exceeding a predetermined amount (a value selected by the Research Team to most likely catch actual impact events and minimize the chance of an overpassing vehicle triggering the system; this value was 0.4 g for most of the monitoring) the datalogger would check the criteria of a scripted *IF* statement, sending an email to a list of recipients. A *Counter* function was included in the email portion of the datalogger program in order to limit the number of emails sent for each event to only one. Without the *Counter*, it would be possible for the datalogger to send more than one email per event. For example, if the accelerometer measured 1.5 g for an impact, the datalogger would send an email, then a split second later, the accelerometer might measure something like 0.65 g (greater than the 0.4 g trigger threshold) as the original impact continued to dampen out. Thus, one impact would have been interpreted by the datalogger program as two impacts, sending two emails. The following is an excerpt from the datalogger program showing the logic of the *IF* statements requisite for an email to be sent. (The entire program script can be seen in Appendix B.)

```
'RESET COUNTER FOR NORMAL VIBRATIONS
If Accmeter < 0.40 Then
   Counter2=0
EndIf
If Accmeter >= 0.40 Then
If Counter2 = 0 Then
   Counter2 = Counter2 + 1
```

For each scan (scan frequency of 25 scans per second was used), the datalogger stepped into the *IF* statements shown above. If the accelerometer measured a value less than 0.4 g, then the email would not be sent and the *Counter* would remain equal to zero. If the accelerometer measured a value greater than or equal to 0.4 g, such as 1.5 g from the example stated above, then the program would make another check to see if the *Counter* was equal to zero. If the *Counter* equaled zero, the datalogger interpreted this as meaning an email had not been sent for the event in question. The datalogger would then add one value to the *Counter's* current value of zero and send the email. Continuing the hypothetical example from above, upon the next scan 1/25th of a second later, the accelerometer value returned might be 0.65 g. This value would meet the first criteria necessary to send an email, *If Accmeter >= 0.40*, however, the *Counter* value would be checked next, being equal now to 1, and the email would not be sent. Once this impact event dampened to less than 0.4 g, the *Counter* would then be reset to a value of 0, making it possible again to send an email for another impact. Figure 3.1 below shows the content of the first version of the email message sent from the datalogger. Figure 3.2 shows the revised email message sent from the datalogger. This email version replaced the first once the feature was added to the WUI allowing the user to access the video files directly from the WUI. As can be seen in Figure 3.2, an active link was included in the second version of the email message that would open the WUI



Subject: Virginia Ave Bridge: Notification of Impact

Warning!

This is an automatic email message from the datalogger at the Virginia Ave Bridge. An alarm condition for impact has been identified. The measured acceleration was 0.5467384g.

Datalogger time was 11/30/2012 09:10:56.20

Figure 3.1 Example of the original email notification sent from the datalogger as immediate notification of impact. Note that the measured acceleration was reported, along with the datalogger's date and time.

through an internet browser, making the video file conveniently available for viewing.

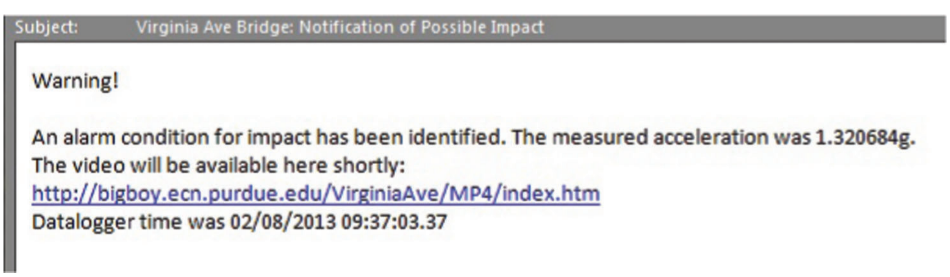
The next notification protocol developed for SPR-3554 was text messaging sent from the datalogger. The datalogger program logic for the text messaging matched the logic used for the email messaging. Essentially, whenever an email message was sent, a text message was also sent. In most cases the text message would arrive just moments before the email message, but for all intents and purposes the two notification protocols performed equally well, arriving within seconds of the impact. Each mobile phone service provider has a unique address to which the message is sent, processed and distributed. These addresses have been listed below for most service providers. The text messages were sent using the same syntax in the datalogger program used for the email messages, except that instead of having an email address, the program had the corresponding text address. For example, if the recipient's service provider and cell phone number were Verizon and 765-555-5555, the address in the program would read, 7655555555@vtext.com.

- AT&T: number@txt.att.net
- Qwest: number@qwestmp.com
- T-Mobile: number@tmomail.net
- Verizon: number@vtext.com
- Metro PCS: number@mymetropcs.com
- Powertel: number@ptel.com
- Boost Mobile: number@myboostmobile.com
- Sprint: number@messaging.sprintpcs.com
- Virgin Mobile: number@vmobl.com
- Nextel: number@messaging.nextel.com
- Alltel: number@message.alltel.com
- Suncom: number@tms.suncom.com
- Tracfone: number@mmst5.tracfone.com
- U.S. Cellular: number@email.uscc.net

The third notification protocol tested during this study was email messaging sent directly from the digital camera. Campbell Scientific's CC5MPX Digital Camera, discussed in more detail below, possesses the ability to capture video (or still image) and attach the file to an email, which can then be sent to a list of recipients over a host email server. The camera email function was successfully tested using the Gmail and Purdue University host servers. The video file is .AVI format, which is supported by a number of free video viewing software; however, it is not supported by Apple mobile devices, such as the iPhone and iPad. In order to view the .AVI video file on an Apple mobile device, inexpensive applications can be purchased to convert the file to a supported format. The advantage of using this notification protocol was that the video file became accessible for viewing as much as 70% (or about 7 minutes) sooner. This was due to the higher data transfer rate available with the digital camera and because the file was delivered in the original .AVI format and not reformatted on the servers prior to being available to view.

3.2 Conclusions for Development of Notification Protocols

Three primary real-time, automated notification protocols were developed and successfully tested throughout the duration of the present study. The three protocols included email messaging from the datalogger, text messaging from the datalogger, and email messaging form the digital camera. The advantage of the first two types of notification was that the warning was received within seconds of the impact occurring. This supported immediate, or real-time,



Subject: Virginia Ave Bridge: Notification of Possible Impact

Warning!

An alarm condition for impact has been identified. The measured acceleration was 1.320684g.
The video will be available here shortly:
http://bigboy.ecn.purdue.edu/VirginiaAve/MP4/index.htm
Datalogger time was 02/08/2013 09:37:03.37

Figure 3.2 Example of email notification sent from the datalogger as immediate notification of impact. Note that the measured acceleration was reported, the datalogger's date and time of event, as well as an active link that connected the user to the web-based user interface where the video file could be accessed approximately 9–10 minutes after receipt of the email.

warning of an impact event that might speed operational and emergency responses. However, video evidence of the impact followed separately about 10 minutes later (using the 4G LTE modem; the time to receipt using the 3G modem was approximately 20 minutes). Thus, the notification was immediate, but the data necessary to make operational and emergency response decisions was slightly delayed. The third form of notification developed does not necessarily meet the definition of "real-time". On average, it was received approximately 3 minutes after the impact occurrence (using the 4G LTE modem; the time to receipt using the 3G modem was approximately 8–10 minutes). However, the advantage of this form of notification was that attached to the email was the video file of the impact in .AVI format, ready for convenient viewing. So, although the *immediate* notification would not be had this way, the video data required to make the operational and safety decisions was received about 70% (or 7 minutes) faster than using the first two protocols.

As a result of this study, the Research Team concluded that the most powerful real-time notification protocol for this specific application would be a combination of two of the three developed herein. Ideally the immediate notification would be received within seconds of the impact (either by email or text messaging), raising instantaneous awareness of the event. That would be followed by the digital camera's video file attached to an email about 3 minutes later. This combination would be able to deliver the most data, the quickest, enabling the transportation officials to make the most rapid corrective response to an incident.

4. TASK IV: BUILD AND INSTALL A PROTOTYPE SYSTEM

A prototype of the web-based bridge monitoring system was developed in Purdue University's Bowen Laboratory and implemented at the Virginia Avenue Bridge over I-65 SB, in Indianapolis, Indiana. Data acquisition equipment was deployed on 11 September, 2012, monitoring through June, 2013. The vertical underclearance of this bridge is approximately 14′0″; as a consequence, the bridge has often been struck by trucks. The SAC desired to better understand the types and frequency of impacts, with a suspicion that some unknown number of impacts was taking place that was not being reported. This suspicion was proven true. The following sections review the major components of the prototype system, including the data acquisition equipment and instrumentation used to capture high definition (HD) video footage of the truck impacts. Figure 4.1 shows approximate locations of each component as it was set up at the actual site.

4.1 Data Acquisition Equipment

The data acquisition system used at Virginia Avenue Bridge consisted of a datalogger, a high-speed 3G cellular modem (replaced by a 4G LTE modem, December 2012), and an omni-directional communication antenna. Figure 4.2 shows the environmental container used to protect the equipment from adverse weather, as well as tampering and theft. The steel container was secured to the scupper pipe, which was already bolted to the abutment wall. The cables seen in Figure 4.2 are power and communication cables extending up to the digital camera (the camera is discussed in detail below). The contents of the container can be seen in Figure 4.3.

4.1.1 Datalogger

The Campbell Scientific CR3000 Micrologger was used to collect the data throughout the duration of the remote monitoring. This rugged datalogger is a high-speed, 16-bit system with a possible analog resolution of 0.33 μV. The CR3000 measures electrical signals from a variety of sensors and can convert the measurement to engineering units, perform calculations, or reduce data to statistical values. An attractive feature of the CR3000 is the ease of programming using Campbell Scientific's Real-Time Data Acquisition (RTDAQ) datalogger support software, making it a versatile platform that can be adapted to a specific need; even for personnel not formally trained in computer programming. RTDAQ is part of a datalogger support software package called, LoggerNet, and is fitted with a program generator where the user is able to configure ports and channels according to a desired specialized application. The software generates a scripted program, based on the user inputs selected from provided menus and options, that can be sent to the datalogger for execution. The program used for the present study is provided in Appendix B. LoggerNet supports the datalogger programming, as well as communication and data retrieval between the datalogger and a PC. This enables the CR3000 to offer remote, real-time data viewing. The datalogger was also equipped with the NL115 Ethernet and Compact Flash

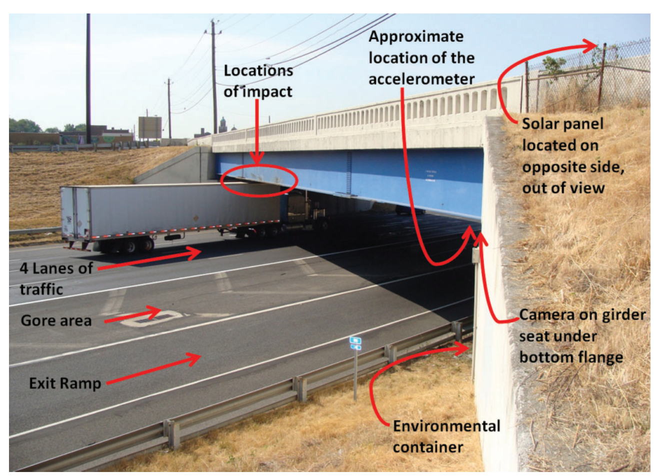


Figure 4.1 Site layout of the prototype system, located at the Virginia Avenue Bridge over I-65 SB.

Figure 4.2 Steel environmental container.

Module. This can be seen in Figure 4.3 above. The NL115 provided for the Ethernet 10/100 connectivity to the datalogger and an internal secure digital (SD) card for onsite data storage.

Another important feature of the CR3000 that was used for the monitoring was the Continuous Analog Out (CAO) ports. The CAO terminals are regulated voltage outputs from 0–5000 millivolts. The datalogger was programmed so that when a predetermined value was measured by the accelerometer on the bridge girder, the datalogger would output a 5000 mV signal to the digital camera. The signal prompted the camera to begin recording video footage. The camera's functionality is discussed more in the following subsection.

4.1.2 Digital Camera

Video footage of the truck impacts on the Virginia Avenue Bridge over I-65 SB were captured using Campbell Scientific's CC5MPX digital camera. The CC5MPX is a high resolution digital network camera designed to meet stringent operational requirements necessary for remote battery powered applications. The robust camera is designed to operate in harsh environments at temperatures between -40°F and 140°F, and comes with an optional heater that can be programmed to turn on to defog/defrost the housing window based upon scheduled photography or when internal temperatures reach a predetermined level. It is capable of 5 megapixel JPG still images and up to 1280×720 (MPEG4) high definition video (up to 30 frames per second). The image and video capture can be accomplished by way of two independent self-timers, an external trigger, motion detection, or via manual command through its web browser interface. The image and video files can be saved to an internal memory card, as well as transferred to a datalogger (using Pakbus or FTP protocols), sent to a PC via email attachment, or direct to a server using FTP.

Another important feature of the CC5MPX camera is the pre-trigger video buffering. The truck impacts occurred at such high rates of speed that even the rapid sub-second response of the camera to the external trigger from the datalogger would not be fast enough to film the entire collision, beginning to end. Thus, the camera was programmed to constantly film, temporarily storing a desired length of video in a memory buffer. If a trigger was not received from the datalogger, that memory buffer would be dumped, and the process would begin again, continuously. When the external trigger was received, the camera would record the memory buffer along with a pre-programmed length of video footage following the trigger event. For the present study, the camera was set to buffer 2 seconds of video, and record another 6 seconds post trigger. Thus, each video file was 8 seconds long and about 4 Mbytes of digital memory. The camera was attached to the girder seat, just beneath the bottom flange, see Figure 4.4. Figure 4.5 shows the vantage point of the camera (Note: the two C-clamps on the girder bottom flange were temporarily installed by the

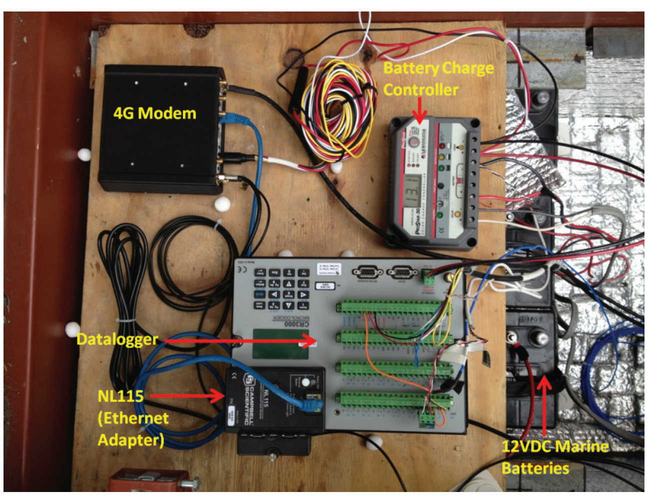


Figure 4.3 Remote data acquisition and communications equipment.

Figure 4.4 Campbell Scientific CC5MPX digital network camera installed beneath the bridge girder.

Figure 4.5 Self-timed hourly photo taken from the digital camera. These photos were posted automatically on the web interface to provide hourly updates of conditions onsite.

Research Team to hold in place the accelerometer used to measure lateral impact). Self-timed, automatic still images were captured hourly and posted on the web interface. This provided the user with a view of the conditions onsite every hour. The interval between the automated still images could be varied from 1 minute to 24 hours, depending on the need. The setting for the photos, as well as all other programmed parameters for the digital camera can be seen in the screen shots of the camera settings provided in Appendix C.

The camera settings can be configured while it is connected locally to a PC via Ethernet cable. Additionally, once the camera has been deployed to the field, settings can be changed remotely through a web browser. This is done by assigning the camera a static internet protocol (IP) address. Utilizing port forwarding on the cellular modem, that IP address can be accessed from the internet by typing the modem's static IP address, followed by a colon and the port number corresponding to where the camera is connected to the modem (i.e., 166.142.27:3002), into the browser address bar, and pushing *Enter*. The browser interface for the camera can be seen in Appendix C.

Lastly, the camera is designed to stream a live video display. Three video definition settings can be selected, 320×240, 640×480, or 1280×720 from the web browser interface. This could be a valuable tool following an impact event where the camera's perspective might show current conditions of the bridge and traffic response, which could be checked immediately following impact notification. This function was activated and successfully tested several times throughout this project. However, it should be noted that at the time of the final report submission, a glitch with the live video camera-browser compatibility was stumbled upon. Campbell Scientific, Inc., technical support was contacted and it was reported that they plan to implement within a year of this report a software upgrade that will eliminate reliance on Active X, improving video cross browser and platform compatibility. It is believed that this change will improve live video performance and remove the existing glitch.

4.1.3 Wireless Communications

A high-speed cellular modem was used to remotely communicate with the datalogger. Two modems were used at separate intervals. The first modem used was an integrated Landcell 882-EVDO Data Modem and IP Router, manufactured by CalAmp. This particular modem has an external 3G cellular broadband router with an integrated dynamic host configuration protocol (DHCP) server, as well as port forwarding capability. The second modem was CalAmp's new Fusion 4G LTE broadband router/modem, which also has an integrated DHCP server and port forwarding. The LTE modem replaced the 3G in December 2012. The SAC favored exploring the capability of the faster 4G LTE data transfer rates, improving the automated notifications and video recovery. The Fusion comes equipped with 3 Ethernet ports (WAN and LAN configurable), GPS, and Wi-Fi capabilities. Additionally, the 4G LTE router can be programed for 3G fallback, or failover, in the event that 4G coverage is lost. Remote connection was accomplished using an assigned static IP address, which was assigned by the cellular service provider. Typing the static IP address of the modem into the web browser address bar and pressing *Enter* connects the PC to the modem, opening a browser interface (see Figure 4.6) where the user can adjust settings and check status, as needed.

The high-speed cellular modem served several purposes, the first of which was to retrieve data remotely. Data were initially collected locally and stored onsite. Then using LoggerNet, installed on a server residing at Purdue University, the data were automatically and routinely downloaded at a predefined interval. The second purpose of the cellular modem was to view live data in real time. This allowed the Research Team to verify that the monitoring system was operating correctly, as well as remotely view the conditions onsite through the camera. One final benefit of the cellular modem was the ability to remotely reprogram the datalogger through the cellular connection. This allowed the Research Team to update and change the program based on the review of incoming data or a shift in the monitoring targets. This capability was especially important in the early monitoring stages when the Research Team was determining the appropriate trigger thresholds that should initiate data recording.

Another important part of the 3G communications equipment was an Ethernet switch. The Ethernet switch was used with the 3G modem to create a local network that interconnected the datalogger and the digital camera to the cellular modem. It basically served as a communications hub facilitating the modem's port forwarding. This enabled the Research Team to access the digital camera independently of the datalogger, and vice versa, for any purpose necessary; one example being when settings or parameters in the camera needed to be adjusted. Note, however, that when the LTE router replaced the 3G router, the Ethernet switch was

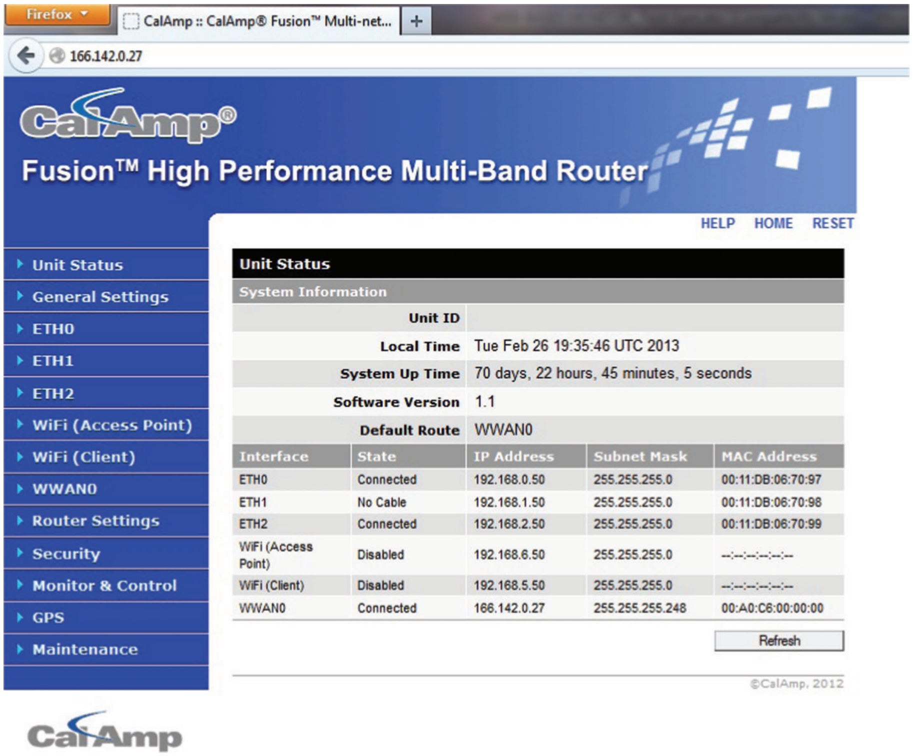


Figure 4.6 Wireless cellular modem browser interface allowing remote configuration and status check.

no longer necessary (and was removed) due to the integrated Ethernet ports on the LTE unit. Thus, the camera and the datalogger were connected directly to the LTE router where the same independent accessibility could still be accomplished.

4.1.4 Power Supply System

The overall power supply system was designed for an indeterminate service life, providing a "drip" charge from photovoltaic (solar cell) panels that counteracted gradual drain of the batteries. The datalogger, digital camera, cellular modem, and Ethernet switch were all powered by 6-deep cycle, 12-VDC marine batteries with capacity for an approximate 5-day reserve. The batteries were housed inside the steel environmental container and wired in series. The Morningstar charge controller ensured that the batteries would not over-discharge, limiting them to no less than 11.7-V, by shutting off the supply to the datalogger and other equipment if the batteries reached that level. This never occurred throughout the duration of the monitoring. Additionally, the charge controller regulated the drip charge coming in from the solar panels, which were deployed specifically to recharge the battery system. Two Kyocera KC120-1 solar panels were installed onsite. The panel installation can be seen in Figure 4.7. Based on guidance from the National Renewable Energy Laboratory (NREL), the solar panels were directed true south and tilted approximately 40 degrees from horizontal in an effort to maximize the equivalent full sun hour exposure during each day. The solar panels were mounted on a 4-inch diameter, schedule 40 steel pipe, using the aluminum UniRac Series 4002 PV Module Rack. With the post planted 36" into the ground with concrete, this application was rated for 90-mph winds. The solar panels were installed on the southern side of the bridge near the wing wall, approximately 40-ft. up the bank from the exit ramp. This location reduced the risk of vehicular collision with the post and solar panels.

Table 4.1 presents the estimated power consumption for each of the major electronic devices. This data was used in calculating the power budget for the solar panel

Figure 4.7 Solar panel assembly used to recharge the battery system.

TABLE 4.1
Power Drain for Each Electronic Device

Device	Approximate Power Consumption @ 12Vdc
CC5MPX Digital Camera	250 mA*
CR3000 Datalogger	15 mA
CalAmp 3G Land Cell Modem	37 mA
Morningstar Charge Controller	10 mA
NL115 Ethernet Adapter	20 mA
Ethernet Switch	260 mA
CalAmp Fusion LTE Modem	410 mA**

*With heater running it drained about 1 A @ 12 VDC in full power mode.
**LTE Modem replaced the 3G Land Cell Modem in December 2012. The power consumption estimate includes the dual band antenna. With the Wi-Fi enabled, power consumption increases approximately 140 mA, for a total of 550 mA.

system to ensure sufficient recharge capacity would be available to sustain the electrical draw on the batteries through the fall and winter months. The tabulated numbers represent actual measured electrical draws, as measured during the in-lab prototype development stage. NREL's *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors* provided the estimated average solar radiation for Indianapolis, Indiana. This data has been provided in Appendix D for convenient reference. There it can be seen that for a tilt equal to latitude, or approximately 40°, the average kWh/m^2/day (Peak Sun Hours) is 2.6 in the month of December. December is the lowest average for the year, thus this number was conservatively used in estimating the power budget.

4.2 Instrumentation: Accelerometer

Impact on the bridge was the targeted parameter. Thus, an accelerometer was employed to detect lateral acceleration of the girder. A PCB Piezotronics model 3711D1FA3G was used. This accelerometer has a sensitivity of 700 mV/g and a measurement range of ± 3 g peak. However, in prototype testing in the Bowen Laboratory at Purdue University, the accelerometer was shown to measure accelerations in excess of ± 5 g peak. The accuracy of the sensor would likely languish at this level of measurement beyond its specified capacity; however, for the current monitoring project upper end accuracy was not as important as functionality. What that means is that the accelerometer was not intended to specifically measure the exact accelerations of the girder due to the impact. Rather, it was employed simply to detect lateral accelerations and provide the datalogger the values it needed to perform its programmed logic. The actual accelerations of the girder were not the objective of the monitoring; rather, the event of impact. The accelerometer provided the means to recognize an impact event. A strain gage or string potentiometer could have also been used for this purpose.

TABLE 4.2
Summary of Prototype Implementation Costs

Hardware/Software	Approximate Cost
CR3000 Datalogger w/NL115	$3800
Modem – CalAmp 3G w/Ethernet Switch	$500
Or Modem – CalAmp Fusion 4G LTE	$1200
Digital Camera	$3000
Steel Environmental Closure	$500
Batteries & Charge Controller	$700
Solar Panels w/Mounting Assembly	$1000
Accelerometer	$200
Misc. Materials (cables, connectors, etc.)	$200
Software (RTDAQ, LoggerNet, RTMC Pro)	$1000
Total	**$10,900–11,600**
Monthly Cellular Service Data Plan	$60

4.3 Summary of Prototype System Costs

Table 4.2 is a summary of the approximate costs of equipment and materials necessary to develop and implement one prototype monitoring system. Note that costs are approximate, do not include labor costs for installation or long term maintenance, nor do they include any type of customer loyalty or quantity discounts. Furthermore, note that software costs would be one-time costs and not repeated for each system implemented.

5. PROJECT SUMMARY AND IMPLEMENTATION

Verification of a real-time, web-based monitoring system developed for the current study was accomplished through real world application at a bridge in Indianapolis, Indiana. The Virginia Avenue Bridge was selected as the candidate bridge for this study due to the fact that it is impacted by passing trucks and/or their cargo relatively often, as depicted in Figure 5.1. INDOT had a total of 33 impacts on record for the bridge's northern most girder (the traffic flow is southbound) as of the start of this study in September 2012. INDOT believed that an unknown number of additional impacts were occurring that were not being reported to the Department.

5.1 Project Summary

Using principles of GUI, off-the-shelf software was used to develop a purposeful web-based interface with condition notification features. It was shown that little or no experience in website construction was necessary to produce a powerful, data-rich interface that was effective and efficient. The construction software used employs a drag-and-drop methodology allowing for simplistic application in generating a data monitoring interface. The WUI developed under the present study can be seen in Figure 2.2. In addition to the WUI, real-time notification protocols were established delivering the capability for immediate notification of impact events. The automated notifications were transmitted over a wireless cellular modem by way of host email servers in the form of email and text messages. The email and text protocols proved highly reliable and were received within seconds of the recorded impact.

The final task completed under SPR-3554 was to implement a prototype system. An accelerometer was temporarily installed on the girder flange to monitor lateral vibrations and was used as the indicator of impact. A Campbell Scientific CR3000 datalogger was stationed onsite to observe the accelerometer values and determine when impact conditions were met. Upon meeting impact conditions, determined by the Research Team, the datalogger transmitted the notifications of impact, while simultaneously triggering a high definition (HD) digital video camera. The camera was installed on the girder seat under the bottom flange of the impacted girder, looking down the length of the girder. The camera was programmed to capture a 2-second video buffer before an impact event, followed by an additional 6 seconds, for a total impact video of 8 seconds per event. The videos provided irrefutable evidence of impact, as well as offering a better understanding of collision severity. The HD videos were available for viewing from PC's and mobile devices anywhere that an internet service provider (ISP) or a 3G/4G wireless network were offered. The monitoring system developed was robust, enduring well the Indiana winter months and fully automated with little or no supervision. Furthermore, the system was self-powered by deep cycle marine batteries, which were recharged using photovoltaic panels with capacity for a 5-day reserve.

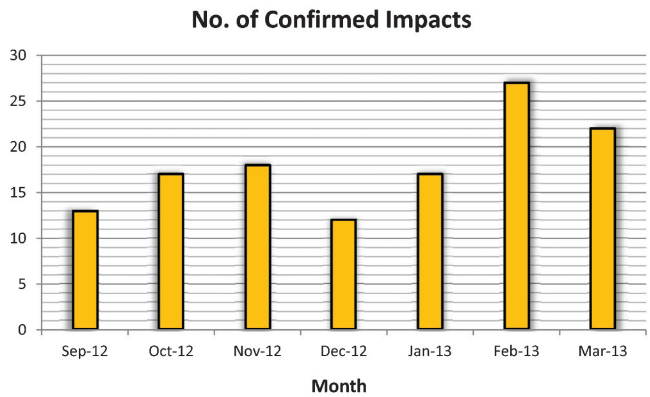


Figure 5.2 Number of confirmed impacts for each month of the study. Note that the study began near mid-September, reducing the possible number of recorded impacts for that month. (Avg./month = 18.2 hits.)

INDOT's suspicion of additional impacts occurring was substantiated. Figure 5.2 shows the number of confirmed impacts with the Virginia Avenue Bridge over I-65 Southbound in Indianapolis, Indiana, as of the date of the present report. The prototype system was deployed to the field on September 11, 2012, thus some impacts were likely missed in the first two weeks of that month. Therefore, excluding September, the average number of impacts per month was over 18. Recall that prior to the deployment of the prototype system, 33 reported impacts were on record, collected over a period of about 4 years (*2*). The monitoring system captured irrefutable data showing that the bridge was actually being impacted more than twice as much as the reported incidents from an entire year, in just one month. In other words, the bridge was being impact loaded more than 26-times as much as was being reported to INDOT. Two examples of these impacts are provided in Figure 5.3 and Figure 5.4.

5.2 Implementation

The implemented prototype provided important insight into actual circumstances of impact loading on

Figure 5.1 Still image taken from HD video footage of a truck impacting the northern girder of the Virginia Avenue Bridge over I-65 SB (note date and time stamp in lower left of image).

Figure 5.3 Image taken from video of a backhoe tractor impacting the Virginia Avenue Bridge in Indianapolis, Indiana.

Figure 5.4 Image taken from video of a bucket truck striking the Virginia Avenue Bridge in Indianapolis, Indiana.

the Virginia Avenue Bridge that was previously unknown. Although bridge girder impact captured on video footage was the targeted bridge parameter for the prototype monitoring system, it should be emphasized that the major components of the system could be adapted for implementation on a variety of bridges, in different and more remote locations, monitoring entirely diverse parameters of interest (e.g. overload, load distribution, fatigue, pier tilt, temperature, etc.). Furthermore, the web-based user interface could be configured to receive real-time data from a network of dataloggers stationed at differing locations throughout the State, or Nation. Thus, a single user interface could be made to concurrently display a multiplicity of data and data types from a number of bridges.

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2. Mickler, J. Personal interview during site visit to Virginia Avenue Bridge, August 2012.

APPENDIX A. EXCERPT FROM SHERMAN MINTON BRIDGE FINAL REPORT

http://docs.lib.purdue.edu/cgi/viewcontent.cgi?filename=1&article=3032&context=jtrp&type=additional

APPENDIX B. DATALOGGER PROGRAM SCRIPT

http://docs.lib.purdue.edu/cgi/viewcontent.cgi?filename=2&article=3032&context=jtrp&type=additional

APPENDIX C. DIGITAL CAMERA SETTINGS

http://docs.lib.purdue.edu/cgi/viewcontent.cgi?filename=3&article=3032&context=jtrp&type=additional

APPENDIX D. PEAK SUN-HOURS DATA FOR INDIANAPOLIS, INDIANA

http://docs.lib.purdue.edu/cgi/viewcontent.cgi?filename=4&article=3032&context=jtrp&type=additional

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

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